Conformal Spacetime from Information: A Gödelian Meter-Stick Problem for It-from-Bit and It-from-Qubit

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"It from Bit" and its quantum cousin "It from Qubit" promise a physics where information is not merely a description of reality but its generator. Yet a persistent metrological obstacle remains: information is dimensionless, while geometry is dimensional. A bridge law can plausibly reconstruct relational structure—causal order, adjacency, and distinguishability—without ever producing a unique meter. This paper embraces that gap as potentially principled rather than embarrassing, in a Gödel-like sense: a system can be internally rich and predictive while leaving one parameter—absolute scale—underdetermined unless an extra axiom is supplied. We propose a two-layer schema. First, an information-first bridge law reconstructs conformal spacetime: the light-cone structure and local "shape" of geometry up to a rescaling. Second, a metrological closure axiom fixes scale by selecting physical standards (clocks and rods) and specifying how they couple to the informational substrate. This reframing clarifies why cosmic expansion does not require an "outside ruler": only dimensionless cross-comparisons of internal standards can decide whether scale drifts universally, runs with coarse-graining, or is tied to particular matter sectors. The result is an experimental research program: identify scale-free invariants, define closure protocols, and test universality across platforms and regimes.

Keywords: Conformal spacetime, It from Bit, It from Qubit, Gödel incompleteness analogy, metrology, meter stick problem, scale factor, conformal geometry, causal structure, distinguishability, information geometry, quantum Fisher information, Bures metric, entanglement adjacency, mutual information, causal order, operational distance, renormalization, running length scale, universality class, clocks and rods, cosmological expansion, dimensionless observables, calibration axiom.

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Art

1. Introduction: Why Information Can Give Cones but Not Meters

The phrase “It from Bit” has survived for decades because it does something rare: it compresses a metaphysical instinct and a scientific ambition into a single memorable line. The instinct is that reality, at its base, may not be made of “stuff” but of distinctions—yes/no answers, outcomes, records, and constraints on what can be known. The ambition is that such distinctions might be sufficient to reconstruct the physical world, including spacetime itself. Yet as soon as one tries to make the slogan do real work, a quiet but decisive technical obstacle appears. Information is fundamentally a matter of counting, and counting is unitless. Geometry, by contrast, is inherently metrical: it is about lengths, times, areas, volumes, and curvature, all of which carry units. In ordinary physics this mismatch is hidden because we inherit a meter stick from the laboratory and a coordinate chart from continuum models. But in an information-first program those inheritances are exactly what must be re-earned.

This paper takes a disciplined position: an information-first approach may genuinely be able to reconstruct the **conformal** or **causal** structure of spacetime—the “cones”—while still failing to reconstruct an absolute “meter” without an additional axiom. That failure is not necessarily a defect; it may be structural. The analogy we will use is Gödel-like: a theory can be internally powerful, richly predictive, and yet leave one degree of freedom unresolved unless a further stipulation is introduced. Here the unresolved degree of freedom is overall scale. If that is correct, then the proper scientific task is not to hide the scale choice, nor to smuggle in Planck-length defaults, but to formalize the split between (i) what information can determine in a scale-free way and (ii) what must be supplied by metrology—by the choice of clocks, rods, and their coupling to the informational substrate.

1.1 The enduring appeal of It-from-Bit and It-from-Qubit

“It from Bit” persists because it offers a reversal of explanatory direction. Instead of saying “physics produces information,” it suggests that information produces physics. The story is attractive for at least three reasons.

First, it fits the practical experience of modern science. Many of our strongest physical laws are expressed operationally: they are recipes for correlating observations, predicting outcomes, and compressing regularities. This encourages the suspicion that “what is real” might be what is stably recordable and communicable—in other words, what is information-like.

Second, the slogan naturally resonates with quantum mechanics. Quantum theory forces a strange intimacy between physical states and the statistics of measurement outcomes. Even without any philosophical excess, quantum mechanics makes it hard to talk about “the world” without talking about what can be distinguished, with what probability, under what measurement constraints. That is why “It from Qubit” feels like a modern sharpening: a qubit is

not merely a yes/no register; it is a structured state space with interference, phase, and compositional nonclassicality. If any informational primitive plausibly underwrites geometry, qubits seem like better candidates than bits.

Third, both slogans speak to an unease about "substance." They promise that the Universe might not require a final inventory of material constituents. Instead, it might be describable as a web of constraints on possible observations and correlations. In that view, spacetime itself becomes a derived bookkeeping device: a stable large-scale summary of the underlying pattern of relations.

However, this appeal can mislead. A slogan can be right about direction (information is deeply tied to physics) while still being noncommittal about mechanism (how information becomes geometry). The core demand of this paper is therefore to replace inspirational directionality with a testable schema.

1.2 The metrology gap: dimensionless information vs dimensional geometry

The metrology gap is simple to state but easy to evade rhetorically: bits and qubits do not come with meters attached.

A "bit" is a unit of information in the sense of a logarithmic count of distinguishable alternatives. It is unitless in the same way that "one octave" in music is a ratio, not a length: it measures comparison, not extent. Likewise, a qubit is a two-dimensional quantum system whose informational capacity depends on measurement context and coding, but the object itself lives in a dimensionless state space. Measures like entropy, mutual information, and distinguishability divergences are all dimensionless numbers. They tell you how many effective alternatives exist, how far apart distributions are, or how strongly systems correlate, but none of those numbers are "meters."

Geometry is different. A metric assigns lengths to curves, times to trajectories, and volumes to regions. Even if one reconstructs a metric up to a scaling factor, the presence of units matters. "Twice as far" is a meaningful relational claim; "one meter" is a metrological claim. Physics needs both, but they play different roles. The relational claim can often be made scale-free; the metrological claim cannot.

In standard practice, we quietly bridge this gap by defining units from conventions tied to physical processes. The modern meter is defined via the speed of light and the second; the second is defined via a specific atomic transition. This is not an embarrassment. It is how operational physics works. But an It-from-Bit program must be explicit about where such a bridge enters. Otherwise, the program commits an unnoticed circularity: it declares that information generates geometry while secretly importing the unit structure from the very physical substrate whose derivation is supposed to be explained.

So the claim “information gives cones but not meters” is not anti-information. It is pro-clarity. The light-cone structure, causal order, and conformal relations are plausibly reconstructible from information-like primitives because they can be expressed in terms of relative distinguishability and influence. The absolute scale—meters—requires an additional act: a calibration or closure.

1.3 The Gödel-like hypothesis: scale as an underdetermined degree of freedom

The Gödel analogy is not a claim that physics is formally incomplete in the same technical sense as arithmetic. It is a structural analogy about underdetermination: some questions cannot be settled by a given set of primitives without adding a further axiom, standard, or coupling rule.

In spacetime physics, there is a natural candidate for such underdetermination: the overall conformal factor. Roughly speaking, causal structure determines “what can affect what” and the shape of light cones, while overall scale determines “how much proper time” and “how much proper length” is assigned to intervals. Many informational reconstructions naturally latch onto causality and distinguishability because those are relational. They are about ordering, accessibility, and separation in an informational sense. But turning that relational structure into a unique metric with meters may require specifying how physical clocks and rods respond to whatever the underlying informational substrate is.

In this framing, the missing meter stick is not merely a missing constant. It is a missing *closure principle*: a rule that connects informational structure to the behavior of concrete standards. If that closure is absent, then scale may remain gauge-like: one can rescale the metric without changing the informational content that the bridge law recovers. The world might still be perfectly well-defined, but “meters” would be a layer of description that depends on how standards are defined and coupled.

This is precisely where the expanding-universe worry becomes illuminating rather than defeating. In cosmology, “distance” is not a single absolute concept. Distances depend on slicing, on which observers you are comparing, and on what you treat as fixed standards. Yet physics proceeds because it focuses on invariants and on operational definitions. A Gödel-like view says: perhaps an information-first reconstruction naturally yields the invariant, scale-free backbone; the metrological layer is then added by specifying standards. If so, the right research question is not “why can’t bits produce meters?” but “what closure axiom makes meters a stable, observer-independent emergent layer at macroscopic scales?”

1.4 Scope boundaries and what we will not assume or import

To keep the argument disciplined, we set boundaries at the start. This paper is not an attempt to solve quantum gravity by slogan substitution. It is an attempt to clarify what an information-first program must specify to become a scientific schema.

We will therefore not assume:

- A black-hole or horizon-based entropy argument as the primary origin of length calibration. Those ideas may be interesting, but they are not required for the conceptual point here, and they can easily function as covert metrological imports.
- A default identification of the information-length scale with the Planck length. That is a choice, not a derivation, unless a specific dynamical mechanism is supplied.
- An "outside the Universe" measuring frame. All claims are to be framed operationally: what internal observers can infer from dimensionless observables and from comparisons among physical standards.
- That a single notion of "distance" is globally meaningful in an expanding universe. We will distinguish local proper-length metrology from large-scale cosmological distance conventions.
- That "It from Bit" must mean classical bits. We will treat "bit" and "qubit" as alternative primitive languages and ask what each can plausibly reconstruct without hidden imports.
- That the bridge law must yield a full metric immediately. A central working hypothesis is that the bridge law yields conformal/causal structure first, and that metrological closure supplies the scale.

Within these boundaries, the goal is modest but sharp: identify what information can plausibly determine without units; identify what must be added to get meters; and reframe the missing step as an explicit closure axiom and an experimental program rather than as an unspoken assumption. That reframing is the paper's foundation.

2. The Meter-Stick Problem Stated as a Formal Ambiguity

If the Introduction framed the meter-stick problem as a conceptual gap, this section tightens it into a formal ambiguity: given only information-like primitives (bits, qubits, events, outcomes, correlations), there are multiple mathematically consistent ways to assign "length," and no purely informational criterion forces a unique choice. The issue is not that "length is unreal," nor that physics is meaningless in a closed universe. The issue is that length, as used in physics, is a compound notion: it mixes (i) relational structure that can be expressed without units and (ii) a metrological convention that fixes scale by anchoring it to physical standards. When those two layers are not explicitly separated, a theory can appear to "derive" meters while actually borrowing them from its hidden coupling assumptions.

Our aim here is to isolate what the ambiguity is, where it lives in standard general relativity, and why it is not eliminated by pointing out that expansion is measurable from within the universe. Expansion is measurable, but only after one specifies the measurement standards. That is the crux: “meters” are not handed to you by information alone; they are extracted by a closure choice that tells you what it means to hold a ruler fixed.

2.1 What counts as “length” inside a closed universe

A “closed universe” in this discussion is not primarily a topological claim (compact spatial slices) and not primarily a cosmological claim (Big Bang, expansion). It is the methodological stance that there is no external reference space in which the universe is embedded. All measurement must therefore be internal and relational. That stance is already the stance of general relativity: spacetime is not a stage sitting inside something larger; it is the total geometric object.

Inside such a universe, “length” can mean at least four different things, and confusion arises when they are conflated:

1. **A geometric length**: a number computed from a metric by integrating along a curve. This is a mathematical object. It becomes physical only when you say how the metric is realized in measurement.
2. **A metrological length**: what a physical rod, constructed from some matter sector, reports when compared to something else. This is an operational notion tied to atomic structure, solid-state forces, and practical definitions.
3. **A relational length**: a statement about ordering or separation that can be expressed as a ratio or as a dimensionless comparison (e.g., “A is twice as far from B as C is from D” in a sense that can be tested without absolute units).
4. **An informational length**: a measure of distinguishability, correlation decay, or causal accessibility, expressed in bits or qubits. This is unitless by construction.

A closed-universe program can often define (3) and (4) without trouble. The problem is converting (4) into (2) in a way that is not merely conventional and not silently circular. If an information-first theory says “a length is a bit-distance,” then it has defined a relational structure. But if it then wants to say “this is one meter,” it must explain why the physical rods built from matter agree with that assignment—and that explanation is a coupling/closure axiom.

So what “counts as length” is not a single primitive fact. It is an agreement between a geometric assignment and the behavior of standards. That agreement is the thing that an information-first framework must earn, not assume.

2.2 Distance notions in GR: proper, comoving, and operational distance

General relativity itself already teaches humility about "distance." It provides a metric, but the mapping from that metric to what an observer calls "distance" depends on observer motion, slicing conventions, and measurement procedure.

Three notions matter for our purposes:

- **Proper distance** is the physical separation between two events or two worldlines measured along a spacelike slice at a chosen time. In a cosmological model, it often scales like a(t) times a comoving coordinate separation. Proper distance is the thing people intuitively mean by "meters right now," but it is slice-dependent: you must choose a notion of "now."
- **Comoving distance** factors out the expansion by using coordinates that move with the Hubble flow. Comoving distances can stay fixed while proper distances grow. Comoving distance is a bookkeeping convenience that tracks large-scale structure, not an immediately measured number on a ruler.
- **Operational distance** is what you infer from a measurement protocol: radar ranging, time-of-flight, parallax, brightness, redshift relations, interferometric phase, and so on. Operational distance is not a single formula; it is a family of procedures. Importantly, operational distances are often derived from **dimensionless** comparisons (frequency ratios, angle ratios) plus a chosen standard of time and/or length.

This distinction matters because "the universe expands" is not a statement that a number called "distance" increases in every sense. It is a statement about how certain operational distances between comoving worldlines evolve relative to chosen standards. If your standards are atomic clocks and rods, expansion shows up as the growth of proper distance between comoving observers in the FRW model. But if you were to define a different standard—some hypothetical rod that itself scaled with a(t)—then the same underlying metric could look "non-expanding" in those units. That is not an argument against expansion; it is an argument that expansion is always described *relative to a metrological choice*.

Therefore, an information-first theory that wants to define length must decide what it is trying to reproduce: proper distance in a particular slicing, operational distance under specific protocols, or a scale-free relational structure that can later be calibrated. The present paper argues for the last option as the clean starting point: reconstruct causal/conformal structure first, then handle metrology explicitly.

2.3 Conformal freedom: what can change without changing causal structure

The “cones but not meters” claim can be made precise by pointing to a well-known feature of spacetime geometry: causal structure is insensitive to certain rescalings.

At the level of intuition: light cones tell you which directions are timelike, null, and spacelike. Those cones determine what can influence what. If you multiply the metric by a positive function Omega(x)^2, the cones remain the same. Angles and causal relations are preserved; absolute lengths are rescaled.

This is the core formal ambiguity relevant to an information-first program: many informational primitives—causal order, signaling constraints, distinguishability relations that track null structure—naturally determine the cone structure but do not determine the conformal factor Omega(x). If your reconstruction is based on “who can signal whom,” you get the causal partial order. If your reconstruction is based on “how outcome distributions change under small displacements,” you may get a local metric shape, but unless you have a calibration that fixes scale, you still have a freedom to rescale lengths.

In a Gödel-like reading, that conformal factor plays the role of the underdetermined degree of freedom. It is not that causal structure is trivial—it is enormously constraining. But it is not the whole story. A theory can lock down causal structure, adjacency, and many dimensionless invariants, while leaving an overall scale field ambiguous unless a metrological closure condition is added.

This is why “derive a length from a bit” is so slippery. You can always introduce a constant l_bit that converts unitless bit-distance into meters. But unless you say what fixes l_bit, you have not eliminated conformal freedom; you have renamed it. And unless you say how l_bit behaves under coarse-graining and across matter sectors, you have not yet produced a physical metric; you have produced a parameterization.

So the conformal freedom is not a technical nuisance. It is the natural mathematical location where “bit-geometry” can stop and “meter-physics” must begin.

2.4 Why “everything expands” is a statement about standards, not a refutation

The objection “everything inflates” is powerful because it targets exactly the metrological layer: if everything expands, what does it mean to say anything has a fixed size? But as soon as you examine what “everything” could mean operationally, you see that it is not a single claim. It is a family of hypotheses about how *standards* behave relative to the large-scale metric.

There are three distinct possibilities:

1. **Expansion relative to atomic standards (the usual physical stance):** comoving separations grow in proper distance as a(t) increases, while atoms and bound structures are stabilized by their internal dynamics. In this case, expansion is measurable internally by comparing cosmological observations to atomic clocks and rods.
2. **Universal scaling of all standards (a strong alternative stance):** all length-setting structures, including atoms, rulers, and the wavelengths of emitted photons at emission, scale in lockstep with a(t). If this were exactly true, much of what we call "expansion" could be reinterpreted as a unit choice. But it would also have implications for dimensionless comparisons (clock ratios, spectral ratios, and the consistency of different standard rulers/candles). It is not a pure semantic move; it becomes a constrained empirical hypothesis.
3. **Sector-dependent scaling (the most general stance):** different physical standards scale differently because different couplings respond differently to the underlying geometry or informational substrate. Then "expansion" becomes a question of which standards you use and how they couple. This stance is dangerous because it can dissolve predictivity unless constrained by invariance principles and cross-checks.

The key point is that "everything expands" is never a pure refutation of measurement. It is a proposal about what is held fixed. Without specifying a standard, the phrase is incomplete. And in a closed universe, standards are not given by an outside ruler; they are given by internal physics. That is why the debate naturally turns into a debate about closure axioms: what physical processes define rods and clocks, and how do those processes couple to the underlying informational reconstruction?

So the stance of this paper is to treat "everything expands" as a prompt to be more explicit, not as a showstopper. If information reconstructs cones, and if rods/clocks fix meters, then the question becomes: do rods/clocks define a scale that is stable across cosmic history, or do they drift relative to the reconstructed conformal backbone? That question is meaningful, internal, and experimentally approachable through dimensionless cross-comparisons. It is also exactly the kind of question an information-first program must address if it wants to graduate from slogan to schema.

3. Bridge Law C: Conformal-from-Information

This section states the core constructive proposal of the paper. The earlier bridge laws (A and B) were presented as ways to go from information to geometry with an explicit calibration constant that turns unitless structure into meters. Bridge Law C shifts the ambition one level "down" in the most productive sense: it claims that an information-first ontology can, in principle, recover the **conformal** structure of spacetime—light cones, causal relations, and a local metric shape—while leaving the absolute scale undetermined until a separate metrological closure axiom is supplied.

The logic is simple. Causality is inherently informational: it is about which events can influence which, what can be signaled, what can be learned, and what cannot. Distinguishability is also informational: it is about whether two situations can be told apart by admissible probes. Both causality and distinguishability can be expressed without units. Together they plausibly fix the "cone geometry" and local angles of spacetime. What they do not fix is the overall conversion from "informational separation" to meters. That is not a defect of the bridge law; it is the very point of the conformal stance.

Bridge Law C should be read as a template, not a single equation. It specifies what must be taken as primitive, what reconstruction is claimed, and what invariances must hold for the reconstruction to count as physical rather than arbitrary.

3.1 Primitive inputs: events, outcomes, and distinguishability relations

A conformal-from-information program needs primitives that are as close as possible to "records" and "comparisons." We will use three:

1. **Events:** a set E of elementary occurrences. An "event" here is not necessarily a spacetime point in the continuum sense. It is a minimal carrier of "something happened" that can stand in relations to other events. In a classical picture, events might be detector clicks. In a quantum picture, they might be measurement outcomes associated with a process.
2. **Outcomes and probes:** a family of admissible probes P, where each probe p maps events (or neighborhoods of events) into an outcome space. Operationally, a probe is a measurement procedure. Formally, it is a rule that assigns to each event-context a probability distribution over outcomes (classical case) or a quantum state/channel description that induces outcome statistics (quantum case).
3. **Distinguishability relations:** for any two event-contexts x and y, and any admissible probe p, there is a quantitative measure of how different the induced outcome statistics are. Denote it generically as D_p(x,y), where D_p is dimensionless. In the classical case,

D_p might be a divergence between distributions; in the quantum case, a distance between states or channels under admissible measurements.

The primitive content of the theory is therefore not “points and coordinates,” but “events, probe-induced statistics, and distinguishability numbers.” This is already close to the informational spirit: it does not assume geometry; it assumes only that comparisons can be made and that some comparisons are more decisive than others.

A subtle but critical point: D_p(x,y) is probe-indexed. If the bridge law is to yield an observer-independent geometry, it must explain how a geometry emerges from a family of probe-dependent distinguishabilities. That is not a nuisance; it is where physics lives. In ordinary practice, different instruments do not agree perfectly at all scales, but they agree in the regimes where we say a stable “geometry” exists. Bridge Law C aims to model that: geometry is what remains after admissibility constraints and coarse-graining stabilize the reconstruction.

3.2 Causal order as the light-cone backbone

Causal order is the most natural candidate for the backbone of the conformal reconstruction because it is inherently relational and because it can be extracted from signaling constraints without importing a metric.

We postulate that the primitive event set E carries a partial order $\prec$ interpreted as “can influence.” Thus a $\prec$ b means that information, signals, or causal influence can pass from a to b under physically admissible processes. This is not merely a logical relation; it is an empirical one: it corresponds to whether interventions at a can change outcome statistics at b, holding fixed the rest of the protocol.

In a continuum spacetime, causal order is tightly linked to the light-cone structure. The order tells you which directions are timelike or null, and it constrains what paths are possible. Crucially, causal order is stable under conformal rescaling: multiplying the metric by a positive function does not change which intervals are timelike vs spacelike vs null. This makes causal order an ideal target for an information-first bridge: it is robust, unit-free, and already lives at the “cone” level.

Bridge Law C therefore begins by treating $\prec$ as primitive or as reconstructible from intervention/response experiments. Once $\prec$ is available, one can attempt to reconstruct a causal topology: neighborhoods defined by causal diamonds, Alexandrov intervals, or other order-theoretic constructs. This supplies a scaffolding on which more refined geometric information can be placed.

However, causal order alone does not give a metric. It gives a conformal skeleton. To get local metric shape (angles, relative scaling in different directions) one needs an additional ingredient: distinguishability.

3.3 Distinguishability as local geometry without units

Distinguishability supplies the "infinitesimal" structure needed to talk about local geometry. The intuition is operational: two event-contexts are "nearby" if no admissible probe can distinguish them well; they are "far" if modest probes distinguish them sharply. This notion is naturally expressed in bits (or nats), not meters.

To turn that into geometry, we need a local approximation principle. For sufficiently close contexts x and y, the distinguishability should behave approximately like a quadratic form in their separation:

$D_p(x,y) \approx (1/2) * g_p(x)(dx,dx)$ for small dx

Here $g_p(x)$ is a probe-dependent positive form on the tangent-like space of variations at x. This is the information-geometry move: divergences between nearby distributions induce a local metric. The key is that g_p is dimensionless. It measures how rapidly outcome statistics change under small displacements in the underlying context.

Bridge Law C uses this not to declare a unique metric, but to extract a **conformal** metric class. The idea is:

- The **directional** structure and angle-like relations in g_p can stabilize across admissible probes and coarse-graining.
- The **overall scale** of g_p need not stabilize, because it can be rescaled by redefining what counts as a unit displacement in the underlying context or by changing metrological closure.

In other words, distinguishability can plausibly give you local shape, but not absolute scale. This is precisely "cones but not meters" stated as a constructive mechanism.

In the qubit version, the same logic uses quantum distinguishability. Local statistical distance between quantum states can induce canonical metrics on state space. The advantage is that the quantum case offers more principled candidates for distance measures that behave well under coarse-graining and admissible operations. But again, the result is still dimensionless geometry unless a closure axiom introduces meters.

3.4 Recovering a conformal class of metrics rather than a unique metric

We now state the central output of Bridge Law C:

- From causal order $\prec$, recover the light-cone structure.
- From stabilized distinguishability geometry, recover local metric shape up to a rescaling.
- Therefore recover a **conformal class** of spacetime metrics rather than a unique metric.

Formally, a conformal class is an equivalence class [g] where g ~ g' if g' = Omega(x)^2 * g for some positive function Omega. Members of the class have the same null cones and causal structure. They differ in "how many meters" are assigned to intervals.

Bridge Law C claims that informational primitives can determine [g] under suitable conditions: enough probes, enough regularity, enough coarse-graining stability. It does not claim that information alone determines Omega(x).

This output has two major consequences.

First, it explains why "minimal length from one bit" is not forced. A bit-based metric gives you a dimensionless separation structure. To turn it into meters you must fix a scale field (a constant in simple cases, a function in general). That scale choice is exactly what metrological closure supplies.

Second, it clarifies the relation to cosmology. An FRW universe can be seen as a conformal geometry plus a scale factor a(t). Much of cosmology's distance ambiguity is precisely about how the conformal backbone is dressed with a scale factor and how standards behave relative to it. Bridge Law C puts that ambiguity where it belongs: in the closure axiom, not in the informational reconstruction.

So Bridge Law C does not weaken the information-first program; it makes it structurally honest. It says: information can plausibly give you the part of geometry that is most robust and most relational. The rest—absolute scale—is an additional layer that must be accounted for explicitly.

3.5 What invariances the bridge law must satisfy to be non-arbitrary

A bridge law that reconstructs geometry from probes and distinguishability can easily become arbitrary if any probe family or divergence measure yields "a geometry." To count as physics, Bridge Law C must respect invariances that enforce stability, comparability, and non-cheating.

We propose five invariance/consistency requirements:

1. **Admissible-operation monotonicity:** if a probe is degraded by a physically admissible processing step (coarse-graining, noise, channel restriction), distinguishability should not

increase. This is the “data-processing” intuition: you cannot gain information for free by forgetting. This constraint strongly restricts what D_p can be and is one reason the qubit upgrade is attractive.

2. **Composition consistency:** distinguishability should compose sensibly across independent subsystems. If two contexts differ in two independent ways, the local geometry should reflect additive or appropriately compositional behavior, at least in the small-displacement regime. Without this, the reconstructed metric becomes instrument-dependent in uncontrolled ways.
3. **Locality / causal compatibility:** the reconstruction must respect causal structure. In particular, changes at a should only affect distinguishability relations in regions that are causally accessible from a under the adopted order. Otherwise the bridge law generates nonlocal geometry that conflicts with the very causal backbone it begins with.
4. **Coordinate / relabeling invariance:** the reconstruction should not depend on arbitrary labels of events or outcomes. If two descriptions are isomorphic as relational structures, they must yield the same conformal geometry. This prevents “geometry by naming.”
5. **Universality under coarse-graining:** perhaps the most important physical requirement: as one coarse-grains to macroscopic scales, different admissible probes and micro-choices should converge to the same conformal geometry. This is the analog of universality classes in statistical physics. If no such convergence occurs, then “geometry” is not emergent; it is a probe artifact.

These invariances do not guarantee success, but they define the standards by which success is judged. They also define the research program: if Bridge Law C is to be more than a philosophical posture, one must exhibit explicit constructions (even toy models) where these invariances hold and where a stable conformal geometry emerges.

Finally, note the conceptual benefit: once Bridge Law C is framed in terms of invariances, the metrological closure axiom becomes sharply separated. Closure is not allowed to arbitrarily reshape cones; it is only allowed to set scale. That restriction makes the whole program falsifiable: if changing standards changes cones, the bridge law has failed. If changing standards only rescales meters while preserving causal relations and macroscopic angles, then the split between “informational geometry” and “metrological scale” has been vindicated.

Bridge Law C is therefore the pivot: it transforms It-from-Bit / It-from-Qubit from an ambition to “derive everything” into a disciplined claim about what information can reconstruct robustly, and what must be supplied by explicitly stated metrology.

4. Bit vs Qubit: What the Quantum Upgrade Actually Changes

If “It from Bit” is the original provocation, “It from Qubit” is the modern pressure test. The temptation is to believe that quantum structure will automatically solve the meter-stick problem by making information “more physical.” But the lesson of the previous section is that the decisive gap is not “classical vs quantum,” it is “unitless vs dimensional.” Quantum information is richer than classical information, and that richness matters: it can constrain what counts as a legitimate notion of distinguishability, it can supply canonical geometries on state space, and it can alter the natural candidates for “what is primitive.” Yet the presence of qubits does not, by itself, generate meters. What it can do is make the conformal-from-information program less arbitrary and more physically disciplined.

This section explains that difference precisely. Bits give you distributions and divergences; qubits give you a structured state space and operational monotonicity constraints; channels and admissible measurements become first-class axioms; entanglement offers an alternate route to adjacency; and still, after all that, overall scale remains underdetermined until metrological closure is specified.

4.1 Classical bit structure: distributions and divergences

A classical bit is, at base, a two-valued random variable. More generally, classical information theory deals with probability distributions over finite or countable outcome sets. In an operational picture, a “state” is identified with a distribution $p(o|x)$ giving the probability of outcome o under context x and a specified measurement procedure. Distinguishability between contexts is then expressed as a divergence between distributions.

This classical setting has three virtues for an information-first geometry program:

1. **Clarity of primitives:** distributions are straightforward objects, and divergences between distributions have well-understood interpretations in hypothesis testing and coding.
2. **Local metric emergence:** for nearby distributions, many divergences induce a quadratic form that functions as a local information metric. This is the classical information-geometry move that motivates Bridge Law A and supports the “local geometry from distinguishability” idea in Bridge Law C.
3. **Operational meaning in bits:** divergences can often be interpreted in terms of error exponents, likelihood ratios, or expected code lengths. They align naturally with “how many bits of evidence” separate two hypotheses.

But classical bits also impose limitations that matter for our thesis:

- **No interference structure:** classical distributions do not encode phase or noncommutativity. Two different physical preparations can yield identical outcome distributions for one measurement but differ for another; classical models can represent this only by expanding hidden state spaces, which tends to reintroduce structural arbitrariness.
- **Probe dependence becomes uncontrolled:** because the classical "state" can be identified only relative to a chosen measurement, the geometry you reconstruct from divergences can become instrument-specific unless you impose strong admissibility constraints by hand.
- **Divergence choice is underconstrained:** there are many divergences, many ways to average across probes, and many ways to define neighborhoods. Without additional principles, classical bit-geometry risks becoming "choose-your-own metric."

These limitations do not invalidate the classical approach. They explain why it tends to produce geometry "up to conventions," which is exactly the kind of ambiguity our conformal program is trying to handle. The classical case demonstrates the problem sharply: bit distances are easy to define, but hard to make canonical.

4.2 Qubit structure: state space geometry and canonical quantum metrics

A qubit is not merely "a bit with extra values." It is a vector state in a two-dimensional complex Hilbert space, and its physically meaningful content is encoded in density operators, Born-rule probabilities, and the transformations that map states to states. Two consequences are crucial for our program.

First, the quantum state space comes with **natural geometries**. There are distances and metrics on the space of quantum states that are not arbitrary inventions but are tied to operational tasks. In the local regime, quantum analogs of Fisher information provide a principled way to define a distinguishability geometry that is less dependent on ad hoc divergence choices. This is exactly what Bridge Law C wants: a local "shape" of geometry derived from distinguishability, but expressed in a way that respects physical constraints.

Second, quantum structure supplies **noncommutativity**, which functions as a natural constraint on what is simultaneously knowable. In a classical model, you can in principle refine measurements to reveal more detail about a hidden state without changing the underlying mathematics. In quantum theory, you cannot. The measurement context is built into the structure. That makes the "admissible probe" idea less arbitrary: the theory itself restricts what probes can exist and how they can be composed.

In plain terms: qubits give you a state space whose geometry is partially fixed by the physics of measurement, not only by our choice of divergence. This is the main sense in which "It from Qubit" is a genuine upgrade for a conformal-from-information program. It does not magically create meters, but it makes the unitless geometry more canonical.

4.3 Channels and admissible measurements: operational constraints as axioms

A key difference between bits and qubits emerges when we stop talking about "states" in isolation and start talking about **processes**. In an information-first ontology, the primitive objects may be less like "points in a space" and more like "transformations and comparisons." Quantum theory is naturally expressed this way because what counts as physically possible is constrained by the structure of quantum channels and measurements.

For our purposes, the upgrade is conceptual: **admissibility becomes part of the ontology.** We no longer say, "pick any probe you like and compute distinguishability." We say, "the set of admissible probes is restricted by fundamental operational constraints." These constraints serve as axioms that discipline the reconstruction.

Examples of what such constraints look like in a theory-agnostic operational language:

- **Monotonicity under admissible processing:** if you coarse-grain outcomes, add noise, or restrict measurement access, you should not increase distinguishability. This prevents a geometry from depending on "unphysical superprobes."
- **Composition rules:** how probes and processes combine across subsystems must be specified, and the geometry must be consistent with that composition. This is essential if we want "space" to be reconstructible as something stable under aggregation.
- **Resource accounting:** if two probes differ dramatically in energy, time, or complexity, then a geometry that treats them as equally admissible may be physically meaningless. A realistic admissibility axiom must include resource constraints or at least acknowledge them as part of the closure layer.

In the quantum setting, these constraints are not mere preferences. They are closely connected to the structure of allowable operations. That is why qubit-based reconstruction has a chance to be less arbitrary: the theory itself provides a built-in notion of what "processing" means and how it limits distinguishability.

This also brings our Gödel-like stance into focus. The conformal structure may be reconstructed from admissible operations and distinguishability relations. But the definition of admissibility may itself contain the seeds of scale: "how energetic may a probe be?" "how fast may it act?" "what bandwidth is allowed?" Those are not purely informational questions. They are precisely where metrological closure will enter if we want meters rather than only cones.

4.4 Entanglement structure: adjacency graphs vs metric distance

Entanglement is often advertised as the bridge between quantum information and geometry. The popular thought is that entanglement "glues space together." Our program requires a more disciplined statement: entanglement and correlations can define **adjacency** or **neighborhood structure**, but adjacency is not automatically a metric, and it certainly is not automatically a metric in meters.

Here is the clean separation:

- **Adjacency graph:** define nodes as subsystems or event-clusters, and define edges by a correlation criterion (e.g., mutual information above a threshold). This yields a graph or network that encodes "who is near whom" in a relational sense.
- **Metric distance:** assign lengths to edges, define geodesic distances, and require consistency conditions that allow continuum approximation. This yields something distance-like, but still dimensionless unless calibrated.

Entanglement can naturally supply adjacency because it is a strong marker of non-separability. But turning entanglement into geometric distance runs into known conceptual issues:

- **Entanglement is not localized:** in many quantum systems entanglement is global and pattern-dependent; it does not behave like short-range adjacency unless special conditions hold.
- **Correlation does not uniquely imply spatial proximity:** two degrees of freedom can be strongly correlated because of common causes, constraints, or global modes, not because they are "near" in a spatial sense.
- **Choice of threshold is a hidden convention:** "one bit of mutual information defines an edge" sounds objective, but the threshold is a metrological choice unless it is justified by universality and stability under coarse-graining.

Bridge Law C can still use entanglement productively, but with a precise claim: entanglement patterns may help reconstruct the conformal adjacency structure—who is connected to whom under influence and distinguishability—while leaving the translation into meters to closure. This is consistent with the idea that conformal geometry is the natural target of information-only reconstruction.

In this view, entanglement helps you find the cones and neighborhoods; it does not, by itself, give you the ruler.

4.5 What remains: scale is still missing without closure

After the quantum upgrade, what remains missing is exactly what our Gödel-like stance predicted: **overall scale**. The quantum upgrade changes what is canonical and what is constrained, but it does not eliminate the need for a closure axiom.

We can now say that with more precision:

- Bits can give you distinguishability numbers and a family of possible local geometries, but they do not select a unique one without extra principles.
- Qubits can give you more canonical local geometries because the state space has principled metrics tied to operational tasks and because admissible operations enforce monotonicity and composition constraints.
- Entanglement can give you relational neighborhood structure that may support a continuum limit.

And yet, in all cases, the output is still a **unitless** conformal geometry unless something fixes scale.

This "something" is not necessarily Planck. It is whatever specifies how physical standards—clocks, rods, transition frequencies, interferometers, resonators—couple to the reconstructed conformal backbone. That coupling is the metrological closure axiom. It is the place where the theory admits: "here is how our unitless relational structure becomes the meter-valued distances of laboratory physics."

In this paper we treat that admission as a feature, not a retreat. It yields a clean architecture:

- **Information reconstructs conformal structure** (cones, angles, adjacency, unitless local metrics).
- **Closure supplies scale** (meters, seconds, and the physical meaning of a fixed rod).
- **Experiments test universality** (whether different standards and probes agree on the same conformal backbone and on stable scale behavior at macroscales).

So the quantum upgrade is worth doing, but for a specific reason: it improves the canonicity and testability of the conformal-from-information claim. It does not dissolve the meter-stick problem. It relocates it to the right place: not in the choice of divergence, but in the coupling between informational structure and physical standards.

5. Metrological Closure Axioms: How Meters Enter Without Planck

Bridge Law C deliberately stops at conformal geometry: cones, causal order, and a unitless local notion of distinguishability. That stop is not a failure; it is a disciplined recognition that "meters" are not natural outputs of counting. The missing ingredient is a **closure axiom**: a rule that states how physical standards—rods and clocks—couple to the informational substrate so that the unitless conformal structure becomes the meter-valued geometry used in laboratory physics.

In ordinary physics, closure is present but invisible. We rarely say "here is the axiom that maps mathematical structure to the behavior of standards" because we inherit stable standards and proceed. But an information-first theory cannot inherit; it must explicitly specify what plays the role of standards and why different standards agree, at least macroscopically. If we do not do this, "meters" enter by smuggling: we unconsciously import a length scale (often Planck) as if it had been derived. The purpose of this section is to show how to introduce meters **without** black-hole arguments and **without** defaulting to Planck, while still keeping the program testable rather than purely conventional.

The central claim is that closure is an explicit, falsifiable part of the theory: it makes predictions about which standards should agree, where they should diverge, how scale might "run" under coarse-graining, and how the resulting metric must behave locally.

5.1 The closure concept: selecting rods and clocks as physical standards

A metrological closure axiom begins with an unromantic fact: physics measures by comparison. "One meter" is not an ontological primitive; it is a relationship between an abstract definition and a physical process that realizes it reproducibly.

In a closed universe, the only available route is internal: choose a class of physical systems whose behavior is stable enough to define units. Historically and practically, that is exactly what we do. Time standards come from atomic transitions; length standards come from time standards plus a conversion constant (the speed of light) or from resonant cavities, interferometers, and engineered solids.

In an information-first framework, the role of closure is to elevate this practical fact into an explicit axiom. The axiom must answer:

- **Which physical processes constitute admissible standards?**
  Are we allowed to build rods from condensed matter? Use atomic transitions? Use photon cavities? Or must "standards" be defined in purely informational terms?
- **What does it mean for a standard to be "fixed"?**
  In a dynamical universe, "fixed" cannot mean "unchanging in an external frame." It must

mean “stable under internal comparisons and reproducible across contexts,” i.e., a standard must define a reliable equivalence class of procedures.

- **How do standards relate to the reconstructed conformal geometry?**
  If Bridge Law C yields only a conformal class [g], then closure must pick a representative metric g_phys within that class by specifying a scale field Omega(x). Operationally, Omega(x) is “what our rods and clocks report.”

Thus closure is the move that selects Omega(x) (or an equivalent scale parameter) by referencing physical standards. It does not invent geometry; it chooses scale consistently with how matter behaves.

5.2 Coupling rules: how standards read the informational substrate

Selecting standards is not enough. One must specify **coupling rules**: how the standards “read” the informational substrate. This is where the closure axiom becomes a genuine law rather than a mere convention.

In the conformal-from-information stance, the substrate provides a relational structure: causal order and unitless distinguishability geometry. The standards are physical systems embedded in that structure. A coupling rule specifies how the behavior of those systems depends on the local informational geometry.

In practice, coupling rules serve three functions:

1. **Scale selection:** given a conformal class [g], the coupling rule determines which metric g_phys corresponds to the trajectories of physical clocks and rods. Equivalently, it specifies Omega(x).
2. **Universality claims:** the coupling rule explains why different standards agree. If atomic clocks and cavity clocks disagree systematically, closure has failed or has become multi-sectoral (with dangerous flexibility). A good closure rule predicts convergence of standards in the macroscopic regime.
3. **Dynamics compatibility:** the coupling rule must allow the standards to remain usable as standards over time. If the standard’s behavior drifts unpredictably with environment or probe choice, then “meters” become unstable and the theory loses empirical traction.

Conceptually, a coupling rule can be stated in either of two styles:

- **Standard-first closure:** declare that a particular standard defines the metric, then derive how other systems behave relative to that metric. This is a metrological choice made explicit.

- **Symmetry-first closure:** require that the metric is the one for which a broad class of standards behave in a locally Lorentz-like way and exhibit universal limiting speeds, isotropy, and stable ratios. This treats closure as an empirical universality constraint rather than a mere convention.

The second style is more ambitious and more compatible with your "experimental quest" framing: closure becomes something to be discovered and tested, not only defined.

5.3 Closure candidates: atomic transitions, cavity modes, condensed-matter scales

If we want closure "without Planck," we must name alternative anchors that are physically meaningful and experimentally accessible, while recognizing that they are still choices. Three candidate families stand out.

1. **Atomic transitions (clock-based closure):**
   Atomic transitions provide extraordinarily stable frequency standards. The modern definition of the second is based on a specific atomic transition, and length can then be derived by meter = c * second / (fixed number). In an information-first framework, atomic closure means: the physical metric is the one relative to which atomic clocks define uniform proper time in local inertial frames. This approach is powerful because it is already how operational physics works; it is also restrictive because it ties scale to one matter sector (atomic structure).

2. **Cavity modes and interferometric standards (field-based closure):**
   Resonant cavities and interferometers define length through electromagnetic standing waves and phase accumulation. This can be framed as "one meter is the cavity length that supports a specific mode at a specific frequency standard." Cavity closure is appealing because it is directly geometric: it ties scale to wave propagation and boundary conditions. It also forces you to clarify how the reconstructed conformal geometry determines propagation and phase—an advantage for conceptual clarity.

3. **Condensed-matter scales (rod-based closure):**
   A solid rod's length is stabilized by interatomic potentials, lattice spacing, and macroscopic rigidity. In practice, rods are inferior to clocks for ultimate precision, but they are conceptually important because they represent "length from matter" rather than "length from light." Rod-based closure makes explicit what is usually implicit: material binding forces define stable standards that do not track cosmological expansion. In the present framework, rod-based closure would specify that the scale factor Omega(x) is chosen so that condensed-matter equilibrium configurations have stable sizes in local proper units.

These candidates are not mutually exclusive. The empirical triumph of modern metrology is precisely that these different realizations agree to extraordinarily high precision once traced to shared standards. For an information-first theory, that agreement becomes a major constraint: closure must be such that atomic, cavity, and condensed-matter standards converge on a common metric at macroscales, even if micro-level probe dependence exists.

The point is not to claim we already know the correct closure. The point is to show that closure can be made explicit without invoking quantum gravity. It can be tied to reproducible physical standards that are already central to measurement science.

5.4 Running scale: l_eff(scale) as a renormalized metrological object

Once closure is explicit, a subtle but potentially crucial possibility becomes visible: the effective conversion between informational separations and physical meters might **run with scale**. This is the natural analog of renormalization in field theory: micro-descriptions can depend on how you coarse-grain, while macro-descriptions flow toward universal fixed points.

In our terms:

- Bridge Law C yields a unitless conformal geometry from distinguishability and causal order.
- Closure introduces a mapping from that unitless structure to meters.
- That mapping may depend on the coarse-graining level at which “meters” are defined.

Thus we introduce the idea of a **running metrological scale**:

l_eff(scale)

This is not Planck-length in disguise. It is a disciplined recognition that “the length corresponding to one bit of distinguishability” could depend on how one defines the probe class and aggregation scale. The goal is not to allow arbitrary drift, but to formalize and constrain it.

A healthy theory would predict something like:

- At small scales, different probe families may induce slightly different effective metrics (probe-dependent micro-geometry).
- Under coarse-graining, these differences shrink, and l_eff(scale) flows toward a stable macroscopic value.
- The macroscopic value is what ordinary rods and clocks report, which is why everyday geometry appears stable and universal.

This structure has an important payoff for the expanding-universe concern. If the cosmic scale factor a(t) evolves, the closure mapping might encode how standards track (or fail to track) that evolution. In other words, what we call "expansion" may partly be a statement about how metrological closure behaves across cosmic time and scale, rather than a purely geometric primitive.

Introducing l_eff(scale) also sharpens falsifiability. If closure requires an uncontrolled, probe-dependent l_eff even at macroscales, the theory fails. If l_eff converges robustly, the program gains credibility as an emergent account of stable geometry.

5.5 Compatibility constraints: closure must preserve local Lorentz-like behavior

Closure cannot be arbitrary. If closure chooses a metric representative g_phys that violates the most robust empirical symmetries of local physics, it is dead on arrival. Therefore, we impose compatibility constraints that any viable closure axiom must satisfy.

At minimum, closure must preserve:

1. **Local inertial behavior:** in sufficiently small neighborhoods, physics must reduce to a form consistent with local inertial frames. Operationally: free-falling standards should not detect preferred directions or preferred frames to leading order. Closure must not introduce a spurious anisotropy into the local metric.
2. **A universal limiting speed:** the existence of an effective "light cone" is central to causal structure. Closure must not permit different standards to disagree about the cone structure itself. If atomic clocks and cavity propagation disagree about null directions, then the separation between conformal reconstruction and closure has collapsed, and the theory becomes inconsistent.
3. **Consistency across standard types:** if closure is defined by one class of standards (say atomic), it must predict why other standards (cavity modes, condensed matter) measure the same local geometry. This is not optional; it is the empirical content of "meters are real" in operational physics.
4. **Controlled deviations only:** if closure predicts deviations (e.g., running scale, probe dependence), they must appear in regimes where they can be bounded and must be small enough not to contradict existing precision tests. The point of allowing l_eff(scale) is not to excuse anomalies; it is to structure the theory's potential novelty so that it yields specific signatures.

These compatibility constraints are the bridge between philosophical restraint and scientific responsibility. They ensure that our two-layer schema—conformal-from-information plus metrological closure—does not become a license for interpretive freedom. Instead, it becomes

a tightly constrained program: recover cones from information; fix meters via explicit standards; require macroscopic universality; and test any deviations as controlled, falsifiable predictions.

In this architecture, “meters without Planck” is not a slogan. It is a precise claim: the metrological closure axiom can be grounded in experimentally realizable standards (clocks and rods) and can be evaluated by whether it preserves local Lorentz-like behavior and yields universality across standards. If it succeeds, the information-first program earns its meter stick without importing quantum gravity assumptions. If it fails, the program has been tested and falsified in a disciplined way—exactly what a serious bridge-law proposal should invite.

6. Cosmological Expansion Reinterpreted as Relative Scale Drift

The phrase “the universe expands” is often heard as a global, almost cinematic claim: space itself is stretching, carrying everything with it. But in a closed-universe framework—general relativity’s own stance—there is no external frame into which the universe grows. Expansion is an internal relational statement, and it is inseparable from the standards by which “distance” and “time” are defined. This is exactly why cosmology becomes a natural stress test for It-from-Bit / It-from-Qubit programs: if your theory cannot say what “meters” mean as standards drift or stabilize, it cannot even cleanly state what it means for spacetime to expand.

In the conformal-from-information architecture, cosmological expansion is reinterpreted as follows. The bridge law reconstructs a scale-free conformal backbone (cones, causal order, and local shape). Metrological closure selects a representative metric by tying scale to rods and clocks. Expansion, then, is not “space growing in itself,” but the dynamical evolution of the scale factor relating (i) the conformal backbone and (ii) the physical standards that define meters and seconds. Put bluntly: expansion is *relative scale drift* between different internal structures, not growth relative to an external ruler.

This section unpacks that stance and shows how it turns an apparent objection (“everything inflates”) into a precise program of internal tests.

6.1 Expansion without an outside ruler: what internal observers can test

Internal observers can test expansion because expansion is inferred from comparisons among internally definable quantities, not from comparison to an external space. The structure of the inference is always the same:

- You specify a class of “comoving” worldlines—observers at rest with respect to the cosmological matter distribution, or at least observers who see the universe as statistically isotropic on large scales.

- You compare signals exchanged between such observers across time.
- You interpret those comparisons using a model of how signals propagate and how standards behave.

The most basic internal signature is redshift: light emitted with some frequency by a source is received with a lower frequency by a distant observer. This is a purely internal, relational fact: it is a ratio of frequencies measured by local clocks at emission and detection. No external ruler is needed.

But redshift alone does not uniquely determine "distance." It determines a relationship between emission and observation that can be interpreted in multiple geometric ways. This is why cosmology uses multiple, mutually constraining probes: angular patterns, brightness relations, time dilation in light curves, and statistical features imprinted in large-scale structure. Each of these is still internal. Each still relies on standards. And each is ultimately a constraint on how the metric evolves relative to the standards that define measurement.

Therefore, the correct statement is not "expansion cannot be confirmed without an outside ruler." The correct statement is: expansion can be confirmed only within a framework that specifies how rods and clocks behave. That is not a defect; it is the operational nature of physics. In our architecture, that framework component is precisely the metrological closure axiom.

6.2 Dimensionless observables as the real experimental currency

A key discipline emerges once we adopt the closed-universe stance: the most robust observational inputs are **dimensionless**. They are ratios, angles, and comparisons that do not presuppose a meter stick. This is not an accident; it is the reason cosmology can be done at all.

Examples of dimensionless observables (stated generically, without committing to a specific dataset) include:

- **Redshift** as a wavelength or frequency ratio.
- **Angular separations** of features on the sky.
- **Relative brightness patterns** once normalized, or brightness ratios across samples.
- **Time dilation factors** inferred from comparing observed time scales of distant events to local analogs.
- **Spectral line ratios** and other dimensionless combinations sensitive to physical constants.

These are the quantities that survive changes of unit conventions and many forms of conformal rescaling. They are also exactly the kind of quantities an information-first bridge law can hope to reconstruct, because they depend more on causal structure and relative scaling than on absolute meters.

This leads to a critical methodological point for the paper: if we want It-from-Bit / It-from-Qubit to be a serious program, we should not start by demanding "derive meters." We should start by demanding: "derive the dimensionless structure that cosmology actually constrains." That structure is largely conformal and causal. Meters enter later, when we choose standards to express the same structure in SI units.

In other words, cosmology's reliance on dimensionless observables is not a weakness; it is an ally. It tells us how to stage the reconstruction: first recover the conformal geometry and invariant relationships; then introduce closure to define the specific metric representative that our rods and clocks report.

6.3 Bound systems and decoupling: what the claim means in closure language

The statement "bound systems do not expand with the Hubble flow" is often misunderstood as a metaphysical claim about absolute size. In closure language, it becomes a concrete operational statement:

- Certain physical standards (atoms, solids, gravitationally bound systems) define stable rods and clocks whose internal equilibria do not track the cosmological scale factor.

But in our architecture, even this statement is not primitive. It is a consequence of how closure is specified and how different dynamical sectors respond to the reconstructed geometry.

To say "a bound system decouples" means:

1. **Its internal dynamics have an equilibrium scale** determined by local interactions (electromagnetic binding, lattice potentials, gravitational virialization, etc.).
2. **That equilibrium scale is stable under the closure mapping**: when you define meters using your chosen standards, the bound system's size remains stable relative to those standards.
3. **The cosmological scale factor primarily affects the separation of comoving, unbound trajectories**, not the internal equilibria of bound structures.

This is not a claim that can be certified by stepping outside the universe; it is a claim about the consistency of internal standards. It becomes testable through cross-comparisons: ranging data, clock comparisons, spectral stability, and consistency among different "ruler" and "clock" realizations.

The important conceptual upgrade is this: decoupling is no longer a vague statement about "space not stretching inside atoms." It is a statement that closure must deliver: the closure axiom must predict that the standards we actually use—atomic and condensed-matter—pick out a scale that is locally stable, and that cosmological expansion shows up in large-scale relations rather than in a universal drift of all internal lengths.

So the claim "bound systems decouple" becomes a **closure constraint**. If closure were chosen such that all internal standards scaled with the cosmological factor, then decoupling would fail by definition. But that closure would then face other observational constraints (next subsection). The program becomes empirical: which closure is consistent with the web of dimensionless observations?

6.4 What "universal scaling of everything" would predict observationally

The hypothesis "everything scales" can be made precise in closure terms: the scale factor Omega(x) that maps the conformal backbone to physical meters is assumed to drift in such a way that all length-setting physical processes scale together. If true in a strong form, it would mean that atomic sizes, resonator lengths, and emitted wavelengths at the source all change in lockstep with cosmological expansion, making expansion partly a unit artifact.

This sounds like it could render expansion unobservable. But it does not. Even strong "everything scales" hypotheses typically produce observable consequences because not all observables are lengths, and not all sectors must scale identically without contradiction. In particular:

- **Dimensionless ratios become the battleground.** If everything truly scaled in lockstep, then many dimensionless ratios would remain constant. But cosmological observations involve multiple independent dimensionless patterns that must remain mutually consistent: redshift relations, time dilation patterns, angular patterns, and the relative calibrations of different standard rulers/candles.
- **Multi-standard consistency becomes restrictive.** "Everything scales" must include atomic clocks, cavity clocks, and condensed matter. If any one of these scales differently, cross-comparisons would reveal drift. If all scale identically, then the hypothesis becomes hard to distinguish from a redefinition of units—until it confronts observations that combine different sectors (for example, propagation effects plus emission physics plus detector physics). In practice, such combined constraints are what make cosmology more than a coordinate convention.
- **Structure formation and dynamics resist pure rescaling.** Even if lengths rescaled, the dynamics of gravitational collapse, virialization, and the growth of structure involve dimensionless combinations of parameters. A universal rescaling that leaves all those

dimensionless dynamics unchanged is not impossible, but it is highly constrained. It is not a free metaphysical move.

The key point for this paper is not to settle the debate here. It is to locate the debate correctly: "everything scales" is a hypothesis about closure and couplings, and it must be evaluated by its consequences for dimensionless internal observations. That is precisely the kind of falsification ladder an information-first program should want.

6.5 Where the bridge law lives: cones from information, scale from closure

We can now say crisply where each piece of the architecture lives in cosmology.

- **Bridge law territory:** causal order, light cones, and conformal relations. These are the structures that govern what can influence what and how signals propagate in a scale-free sense. They are closely aligned with dimensionless observables and with the operational logic of cosmological inference.
- **Closure territory:** the selection of a representative metric in meters and seconds, via rods and clocks and their coupling rules. This is where the cosmological scale factor becomes "the scale factor measured in our units," and where questions about drifting standards, decoupling, and universality are decided.

This separation has two large benefits.

First, it rescues It-from-Bit / It-from-Qubit from a common trap: the trap of promising a derivation of meters from information and then collapsing into Planck-scale defaults. Instead, the program can make a strong but realistic claim: information determines the conformal backbone; meters enter through closure; and cosmology is where closure is most severely constrained and most clearly testable.

Second, it turns the expanding-universe worry into a guiding constraint: any closure axiom must (i) preserve the cone structure reconstructed by the bridge law, (ii) yield stable local metrology consistent with local Lorentz-like behavior, and (iii) produce a cosmological scale drift consistent with the full set of dimensionless observational cross-checks.

In this view, expansion is not a refutation of the meter-stick program. It is the proving ground. If we can specify a conformal-from-information bridge law and a non-Planck closure axiom that together reproduce the internally testable features of cosmology—without smuggling in the result—then the slogan "It from Bit / It from Qubit" has advanced from poetry to schema.

7. An Experimental Research Program: What to Measure

Up to this point the argument has been structural: information can plausibly reconstruct conformal geometry (cones, causal order, unitless local shape), while meters enter through an explicit metrological closure axiom tied to physical standards. The natural next question is: how could such a two-layer picture be tested? This is where the paper becomes intentionally practical. We do not need a fully completed "theory of everything" to begin testing whether geometry is, in some operational sense, reconstructible from information. We need a disciplined program that identifies measurable invariants, isolates where scale enters, and determines whether different instruments converge on a shared conformal backbone.

The central principle of the experimental program is to **separate what should be scale-free from what should depend on closure**, then measure both. If the conformal-from-information claim is right, the scale-free sector should show universality across standards and probes (within controlled limits). If the closure axiom is right, the scale-setting sector should be consistent across distinct realizations of rods and clocks, and any drift should be constrained, structured, and coarse-graining stable.

In this section we outline what to measure, how to interpret it, and what a minimal "reference implementation" should output so that independent groups can reproduce and falsify the claims.

7.1 Scale-free invariants: causal structure tests and conformal observables

The first targets should be invariants that do not require a meter stick at all. These are the observables most naturally associated with the bridge law itself.

Two families dominate:

1. **Causal structure tests:**
   These ask whether the inferred ordering of influence and signaling constraints is consistent with a stable cone structure. In operational terms, you do interventions: perturb something "here," ask where changes can be detected "there," and map out an empirical partial order. The minimal deliverable is not a distance; it is an order relation and a causal neighborhood structure.

Causal tests can be phrased as questions like:

- Can an intervention at event a change the distribution of outcomes at event b under admissible controls?
- Does the observed influence relation satisfy transitivity and antisymmetry in the regime of interest?

- Are there empirically detectable violations of cone-like propagation (suggesting nonlocality or hidden channels)?

These are scale-free in the sense that they can be expressed purely as “possible vs impossible” influence patterns and conditional dependency structures.

2. **Conformal observables:**
   Conformal structure includes angles and null structure but not absolute scale. Operationally, conformal observables are quantities that remain invariant under rescaling of the metric by a positive function.

In practice, conformal observables show up as:

- **Ratios** of propagation times under standardized protocols (not absolute times),
- **Angular patterns** and relative directions inferred from multi-signal triangulations,
- **Relative ordering and nesting** relations among causal diamonds or light-cone intersections,
- **Normalized correlation profiles** where only the shape matters, not the absolute length scale.

For the experimental program, the goal is to find observables that different labs and platforms can measure and that should agree even if their absolute calibrations differ. Agreement here would support the claim that there is a robust conformal backbone that is accessible from information-like data.

7.2 Cross-standard comparisons: clock ratios, spectral ratios, and drift tests

Once the scale-free sector is mapped, the program moves to the heart of metrological closure: different standards must agree on scale, or else we do not have stable “meters” in the ordinary sense.

The most powerful tests are **cross-standard ratio tests** because they are dimensionless and therefore do not require an external absolute reference. They ask whether distinct clocks and rods drift relative to one another.

Three particularly clean classes are:

1. **Clock ratio stability:**
   Compare two different clock technologies over time and conditions. The output is a time series of the ratio f_A/f_B. If closure is universal and stable, this ratio should be constant up to understood environmental effects and noise. If closure is sector-dependent or drifting, the ratio will show systematic deviations.

2. **Spectral ratio stability:**
   Compare spectral line ratios in controlled environments and across conditions. Again, ratios are dimensionless. This class of tests probes whether the "physical standards" implicit in atomic structure remain stable or drift relative to other standards.

3. **Drift under scale separation:**
   A closure axiom that involves a running scale l_eff(scale) predicts that the mapping from unitless distinguishability to meters could depend on coarse-graining or on the characteristic length/time scale of the probe. Drift tests therefore compare standards operating at different scales (e.g., different frequency bands, different resonator sizes, different interrogation times) and look for systematic, scale-linked discrepancies that cannot be explained by known systematics.

The key deliverable here is not just "no drift." It is a structured residual analysis: what drift is observed, how it depends on environment and scale, and whether it is compatible with a single closure mapping or demands a multi-sector closure (which is possible but dangerous because it can dissolve predictivity).

7.3 Probe dependence: when different channels induce different micro-metrics

Bridge Law C allowed the possibility that at microscopic levels, different probes might induce slightly different local distinguishability geometries—different "micro-metrics." This is not automatically a failure. It is a realistic acknowledgement that what counts as distinguishable depends on the accessible channels.

The experimental task is to determine whether probe dependence is:

- **Pathological:** geometry changes wildly with probe choice, making reconstruction arbitrary.
- **Controlled:** micro-metrics differ, but differences shrink under coarse-graining and converge to a shared conformal geometry macroscopically.

To test this, you must intentionally vary probes:

- Change the measurement basis or observable family (in quantum systems).
- Change the noise model or channel bandwidth.
- Change the resource constraints (time, energy, number of samples) in controlled ways.

Then compute the inferred local distinguishability geometry from each probe family and compare:

- Do they agree on causal order and cone structure?

- Do they agree on conformal observables (angles/shapes) after rescaling?
- Do discrepancies correlate with understood resource limits and processing monotonicity?

The important output is a **probe-equivalence class**: the set of probes that, under coarse-graining, yield the same conformal geometry. If the equivalence class is empty or too narrow, the program is likely not describing emergent geometry; it is describing instrument artifacts. If the class is large and stable, the conformal-from-information claim gains substance.

7.4 Coarse-graining studies: stability and universality across scales

Coarse-graining is where "emergence" becomes a measurable claim. The two-layer architecture predicts that:

- Conformal geometry should become more probe-independent at larger scales.
- Scale-setting closure should approach a stable macroscopic limit, even if micro-level l_eff(scale) runs.

Therefore, the program must include explicit coarse-graining studies:

1. **Spatial or graph coarse-graining:**
   Aggregate events into clusters, or nodes into supernodes, and repeat the reconstruction. Track whether inferred causal order and conformal observables stabilize.
2. **Temporal coarse-graining:**
   Increase integration times, average over more cycles, and test whether reconstructed structures converge.
3. **Information coarse-graining:**
   Apply admissible processing (binning outcomes, compressing records) and verify monotonicity: distinguishability should not increase, and reconstructed cones should not distort unpredictably.

The key concept is **universality across scales**. A successful emergent geometry program should show that, beyond some scale, the reconstruction becomes insensitive to micro-details and yields a stable conformal structure. This is not optional; it is the empirical meaning of "spacetime" as a robust macroscopic object.

In the language introduced earlier, coarse-graining studies aim to estimate whether there is a convergent l_eff(scale) and a stable conformal backbone. They also supply a falsification path: if no convergence occurs, or if convergence requires ad hoc probe tuning, the bridge law is not doing physical work.

7.5 Data requirements: what a “reference implementation” must output

To keep this program from becoming purely rhetorical, we specify what a minimal “reference implementation” should output. This is not a software mandate; it is a reproducibility standard. If independent teams cannot reproduce your reconstruction from the same class of inputs, you do not have a testable framework.

A reference implementation should output, at minimum:

1. **Event and probe specification:**
   A clear description of what constitutes an event, what probes were used, and what admissibility constraints apply. This includes resource constraints that materially affect distinguishability.

2. **Causal structure inference:**
   An inferred partial order or causal graph with confidence measures. Include diagnostics for violations of cone-like constraints and sensitivity to intervention assumptions.

3. **Local distinguishability geometry:**
   A local metric-like object (unitless) inferred from probe statistics, including uncertainty estimates. If multiple probes are used, output probe-indexed geometries and their relations.

4. **Conformal class summary:**
   A representation of the conformal geometry that is invariant under local rescaling, plus a method for comparing conformal structures across runs and across probe families.

5. **Closure mapping outputs:**
   If closure is applied, output the inferred scale mapping parameters, such as Omega(x) or an equivalent scale field, and/or an estimated l_eff(scale) curve. Provide confidence intervals and sensitivity analyses.

6. **Cross-standard comparison logs:**
   Time series of dimensionless ratios (clock ratios, spectral ratios, resonator comparisons), with corrections applied and residuals reported.

7. **Coarse-graining convergence diagnostics:**
   Quantitative plots/tables (conceptually) that show how reconstruction outputs change under coarse-graining. The point is to demonstrate stability or reveal failure modes.

8. **Falsification flags:**
   Pre-registered failure criteria: thresholds for probe dependence, nonconvergence,

symmetry violation, or inconsistency across standards. A framework that cannot specify what would falsify it is not yet physics.

With these outputs, the experimental program becomes concrete: it defines what is measured, what is reconstructed, what is expected to be invariant, and how deviations are interpreted. Most importantly, it avoids the trap of demanding "meters from bits" in one leap. It treats the conformal backbone as the first measurable target and treats meters as the product of an explicit closure map that can be tested via cross-standard ratio experiments. That is precisely the kind of scientific posture required if It-from-Bit / It-from-Qubit is to mature from an inspiring metaphor into an empirically disciplined research agenda.

8. Internal Consistency Tests as a Formal Test Suite

A bridge-law program is not credible merely because it sounds operational. It becomes credible when it can be turned into a formal test suite: a set of consistency checks that any proposed reconstruction must pass in order to be considered "spacetime-like" rather than an artifact of arbitrary probe choices, data processing, or modeling convenience. This section defines such a suite.

The key methodological shift is this: instead of asking, "Does the reconstruction look like a metric?" we ask, "Does the reconstruction behave like a physical geometry under the operations that physical theories must tolerate?" Physical geometry must be patchable, locally consistent, approximately Lorentz-like in the right limits, stable under coarse-graining, and capable of producing continuum-like constructs (geodesics and curvature) when appropriate. If those conditions fail, then the conformal-from-information claim is not merely incomplete; it is incorrect as a model of emergent spacetime.

The test suite is internal in the sense that it does not require an external ruler. It requires only the ability to compare reconstructions across overlapping regions, probe families, and coarse-graining levels, and to check whether the outputs satisfy structural identities expected of a coherent geometric object.

8.1 Locality and composition: patching reconstructions without contradiction

Any geometry intended to represent a world must be patchable. In practice, this means you can reconstruct geometry from data collected in region A and from data collected in region B, and if A and B overlap, then the reconstructions agree on the overlap up to the allowed gauge freedoms (in our case, up to conformal rescaling).

This yields a concrete set of tests:

1. **Overlap agreement test:**
   Reconstruct conformal geometry on A and on B independently. Restrict both reconstructions to A ∩ B. Do they match after applying an allowed conformal transformation? If not, the reconstruction is not describing a single underlying conformal geometry.

2. **Gluing consistency test:**
   Attempt to glue the reconstructions on A and B into a single global object. This is more than overlap agreement; it asks whether the transition functions between patches are coherent. In a successful conformal reconstruction, the "transition" between patches should not require arbitrary, data-dependent distortions beyond conformal freedom.

3. **Composition test across subsystems:**
   If the event set can be factored into subsystems (or if multiple detectors/agents contribute), reconstruct geometry from each subsystem and then from their composition. The composite reconstruction should be compatible with the individual reconstructions, with differences explainable by increased information access rather than contradiction.

4. **Local intervention compatibility:**
   Local changes (interventions, perturbations) should have effects consistent with causal locality. In particular, interventions should not force geometric changes in causally disconnected regions, except through known inference artifacts that must be explicitly bounded.

These tests collectively enforce a key principle: geometry must not be an artifact of the reconstruction boundary. If the output depends sensitively on where you "cut" your dataset, you have not found emergent spacetime; you have found an inference instability.

8.2 Lorentz-like symmetry: preferred-frame diagnostics in reconstruction outputs

Because Bridge Law C aims to reconstruct the conformal (cone) structure, it must be especially vigilant against preferred-frame artifacts. If the reconstructed cones and local shapes encode a hidden absolute time direction or a laboratory-specific anisotropy, then the output is not plausibly spacetime-like in the sense that we observe.

The test suite therefore includes preferred-frame diagnostics:

1. **Cone isotropy test:**
   In a locally inertial regime, the reconstructed null directions should be isotropic up to expected noise and environment. If null cones consistently appear "squeezed" in a

direction tied to the apparatus, reconstruction may be encoding instrument bias rather than geometry.

2. **Boost consistency test (operational):**
   Perform reconstructions under changes of motion state of the apparatus when possible (or simulate effective boosts through controlled changes of signal timing and directionality). The reconstructed cone structure should transform consistently, not reveal a fixed background frame.

3. **Clock/propagation coherence:**
   Null structure inferred from signal propagation must agree with causal structure inferred from intervention/response relations. If one indicates superluminal influence relative to the other, the reconstruction is internally inconsistent.

4. **Anisotropy residual analysis:**
   Any systematic anisotropy in the reconstructed conformal geometry should be decomposed into known sources (e.g., medium anisotropy, detector geometry, noise covariance). If residual anisotropy persists in regimes where it should vanish, the bridge law is either incomplete or wrong.

These tests are crucial because an information-based reconstruction can easily smuggle in preferred structure through the choice of probe family, the sampling pattern, or the data-processing pipeline. Lorentz-like behavior is not assumed here as dogma; it is treated as a highly constrained empirical regularity that any spacetime-like reconstruction must reproduce in the appropriate regime.

8.3 Continuum emergence: geodesics, curvature surrogates, and convergence

A conformal reconstruction is not yet a full geometric theory unless it supports a continuum approximation where appropriate. Continuum emergence is therefore tested by asking whether standard geometric notions can be approximated in a stable way as one increases data density and coarse-graining.

Three targets define the continuum test suite:

1. **Geodesic surrogates:**
   In a metric geometry, geodesics are locally extremal paths. In a conformal setting, null geodesics are especially meaningful because they depend only on the conformal class. The reconstruction should permit identification of “preferred” causal paths that behave like geodesics in the dense-data limit.

Operationally: you examine chains of events that maximize causal reach or minimize distinguishability distortion, and you test whether those chains converge under refinement to stable trajectories.

2. **Curvature surrogates:**
   Curvature in the usual sense requires a metric with scale, but conformal geometry still supports curvature-like invariants and, more generally, tests for non-flatness in the relational structure. The program can define curvature surrogates as measures of non-additivity, triangle-like distortions in distinguishability, or holonomy-like inconsistencies when transporting local frames around loops (under whatever transport rule the reconstruction defines).

The test is not "compute the Ricci scalar." The test is: do curvature surrogates converge and behave consistently across probe families and patch choices?

3. **Convergence under refinement:**
   Continuum emergence demands that as you increase data density, enlarge the event set, or refine probe resolution, the reconstructed conformal object stabilizes rather than drifting unpredictably. Convergence diagnostics are not decorative; they are the operational meaning of "a geometry exists."

A successful outcome is not perfect smoothness. It is a demonstrable flow toward a stable conformal structure and stable geometric surrogates as sampling improves and coarse-graining is varied.

8.4 Failure modes: underconstrained probes, discretization noise, non-universality

A formal test suite must anticipate how the program can fail. Naming failure modes is not pessimism; it is how one prevents a framework from becoming unfalsifiable.

We highlight four dominant failure modes:

1. **Underconstrained probes:**
   If the admissible probe set is too narrow, then many geometries fit the data. The reconstruction may appear to "work" but is actually non-unique. Symptoms include high sensitivity to small probe changes, large gauge-like freedoms beyond conformal rescaling, and lack of stable overlap agreement.

2. **Discretization artifacts:**
   If the event set is too sparse or too irregular, inferred structures can reflect sampling geometry rather than physical geometry. Symptoms include apparent anisotropies aligned with sampling grids, false causal asymmetries caused by detection thresholds, and failure of convergence under refinement.

3. **Non-universality across probes:**
   If different probe families yield different cone structures or incompatible conformal geometries even after allowed transformations, then the program is describing instrument-dependent "effective geometries" rather than a shared spacetime-like object. Probe dependence is acceptable only if it is controlled at micro-scales and converges macroscopically.

4. **Closure leakage into cones:**
   The architecture requires that closure fix scale without altering the cone structure derived from information. If, in practice, changing standards changes the inferred cones, then the supposed separation between bridge law and closure has collapsed. This is a decisive failure because it means the "conformal" backbone is not actually reconstructible from information alone; it is being shaped by metrology in an uncontrolled way.

These failure modes are the reason the earlier invariance requirements were emphasized. A successful conformal-from-information program must not merely reconstruct something geometry-like; it must show that its output is robust against these well-known routes to false positives.

8.5 Falsification ladder: what would kill the conformal-from-information claim

To keep the program in the domain of physics rather than metaphysics, we specify a falsification ladder: increasingly stringent criteria whose failure would progressively weaken, and eventually kill, the conformal-from-information claim.

A proposed ladder is:

Level 1: Non-uniqueness beyond conformal freedom
If, even in controlled settings, the reconstruction is not unique up to conformal rescaling—i.e., many incompatible cone structures fit the same data—then the bridge law fails at its basic promise. It has not extracted even conformal geometry from information.

Level 2: Patch inconsistency
If reconstructions on overlapping regions cannot be glued coherently (even after allowed conformal transformations), then there is no single emergent conformal object. The output is an artifact of boundary choices or inference instabilities.

Level 3: Probe non-universality at macroscales
If, after coarse-graining to scales where universality is expected, different admissible probe families still yield incompatible cone structures or incompatible conformal observables, then the

theory has not reconstructed spacetime; it has reconstructed probe-specific effective relations with no stable geometric limit.

Level 4: Persistent preferred-frame artifacts in regimes expected to be Lorentz-like
If the reconstructed cones exhibit systematic anisotropy or preferred directions tied to apparatus or environment, and these cannot be eliminated by known corrections or bounded as small effects, then the bridge law is not recovering physical cone structure. It is encoding measurement bias into geometry.

Level 5: Closure alters cones
If changing metrological standards changes the inferred cone structure, then the architecture collapses. The separation "cones from information, meters from closure" is false in the model. At that point the conformal-from-information claim, as stated, is killed.

Level 6: No convergence under refinement
If increasing data density and improving measurement resolution does not lead to convergence of conformal observables and geometric surrogates, then there is no emergent continuum-like conformal structure. The claim fails not because of noise, but because the supposed geometric object does not stabilize.

The virtue of this ladder is that it allows the program to be tested in stages. Early failures can teach what constraints are missing or what probe families are inadequate, while late failures would decisively rule out the central claim. A theory that survives the higher rungs of the ladder would have accomplished something meaningful: it would have shown that a spacetime-like conformal structure can, in fact, be reconstructed from information-like primitives in a robust, instrument-independent way. That would not complete the story of meters, dynamics, and closure—but it would secure the hardest and most foundational step: making the cones real without importing the ruler.

9. Implications for Quantum Foundations and Measurement

If the earlier sections built a structural and experimental program, this section points to the philosophical and foundational payload: the conformal-from-information architecture does not merely reinterpret meters; it reinterprets measurement. In the usual narrative, spacetime is "there," and measurement reveals properties within it. In an information-first narrative, measurement is not a passive window—it is an active process that creates durable records and thereby supplies the raw material from which geometry is inferred. This does not collapse physics into idealism. It does not say "mind makes the world." It says something more disciplined and, in a sense, more severe: *only what can be recorded and stably compared can serve as geometry for internal observers.*

This stance also sharpens the meaning of "information is physical." In many discussions, that phrase becomes a vague slogan about thermodynamics or computation. Here it becomes a constraint: if information truly grounds geometry, then the mapping from informational structure to meters (closure) must be consistent with what physical measurement and record-making can actually do. Closure is no longer a free conversion constant. It is constrained by the operational possibilities of measurement apparatus, by quantum limits on distinguishability, and by the requirement that many distinct standards converge on a single macroscopic geometry.

The upshot is a new split: informational structure is the conformal backbone; metrological scale is a closure layer tied to how records are made and stabilized. This section unfolds those implications in five parts.

9.1 Measurement as record-making that enables geometry reconstruction

In the conformal-from-information picture, measurement has a dual role:

- It produces **outcome statistics** (probability distributions or quantum state updates) that define distinguishability.
- It produces **records** that persist long enough to be compared across time, locations, and instruments.

Geometry reconstruction requires both. You cannot reconstruct a causal order or a conformal neighborhood structure from ephemeral outcomes that cannot be reliably stored, transmitted, or cross-checked. Thus measurement is not merely "sampling a pre-existing geometry." It is the process that generates the stable relational data from which internal observers infer geometry.

This suggests a foundational reframing:

- A "spacetime event" is not primarily a coordinate point. It is a record-bearing occurrence—something that can enter into later inference as a node in the causal/relational network.
- The "line element" is not primarily a primitive metric quantity. It is a limit object derived from how rapidly records and outcome statistics change under admissible variations.

This is not the same as saying "measurement creates reality." It says: geometry, as *known and used by internal agents*, is a compression of record structure. Where records are impossible (because of extreme noise, no stable memory, or fundamental quantum constraints), geometry becomes operationally underdetermined. That operational underdetermination is not an embarrassment; it is the measurable boundary of what "space" can mean.

This also explains why the earlier emphasis on coarse-graining and universality matters. Records become stable only after sufficient redundancy, error correction, and environmental robustness.

A geometry built from records is therefore naturally emergent: it is sharp at scales where record-making is robust, and fuzzy at scales where it is not.

9.2 Observer role without idealism: apparatus constraints define admissibility

The word "observer" triggers idealist anxieties, so we discipline it. In this paper, "observer" means an **apparatus-plus-protocol** capable of producing records and comparisons. The role of the observer is not metaphysical; it is operational. The observer matters because different apparatuses allow different measurements, and admissibility constraints define what can be distinguished.

Quantum mechanics makes this unavoidable. You cannot simultaneously measure all observables; you cannot clone unknown states; and you cannot extract unlimited information without disturbance. Therefore, the set of admissible probes is not an arbitrary choice—it is physically restricted. In our architecture, those restrictions become part of the theory's foundation.

This yields a principled middle position:

- We do not say "the mind chooses reality."
- We do say "the apparatus defines the accessible sigma-algebra," i.e., the space of outcomes and the transformations that preserve operational meaning.

Thus, the "observer" enters the bridge law only through admissibility: what measurements are physically possible, what resources they require, and how they compose. The geometry we reconstruct is the geometry that is stable under the admissible probe class. That makes the program empirically grounded: if you change the apparatus in a way that should not matter macroscopically, the reconstructed conformal geometry should not change. If it does, the program fails at universality.

This also clarifies why closure must be explicit. Rods and clocks are not abstract; they are physical apparatuses. The closure axiom is therefore a statement about which apparatuses count as standards and why their readings should agree. In that sense, "observer constraints" are not philosophical decorations; they are the empirical content of metrology.

9.3 Entanglement as neighborhood: when correlation geometry approximates space

Entanglement often enters these discussions as a kind of mystical glue. In this paper, it has a precise, limited role: entanglement and correlations can supply **neighborhood structure**—a graph of adjacency—under conditions where correlation patterns behave like locality.

The key qualifier is "under conditions." Correlation does not automatically equal spatial proximity. Two degrees of freedom can be highly correlated for reasons unrelated to spatial

adjacency: common causes, global constraints, conservation laws, or engineered couplings. Therefore, correlation geometry approximates space only when additional structural conditions hold, such as:

- **Decay structure:** correlations fall off in a way that supports a notion of near vs far.
- **Compositional locality:** combining subsystems preserves adjacency relations rather than producing ubiquitous long-range ties.
- **Stability under coarse-graining:** neighborhood relations become clearer, not noisier, as you aggregate degrees of freedom.

When those conditions hold, entanglement can help identify a network whose large-scale limit can resemble a manifold-like geometry, at least conformally. In our program, entanglement is then a candidate informational primitive for reconstructing neighborhoods and cones, not for fixing meters.

This is where It-from-Qubit adds real value: quantum correlations carry richer structure than classical correlations, and the constraints on quantum operations help restrict which correlation patterns are physically realizable. That can reduce arbitrariness in the reconstructed adjacency graph and increase the chance of universality.

But the central thesis remains: adjacency is not meter distance. Even if entanglement reconstructs neighborhood structure beautifully, the translation into meters still requires closure—some linkage to physical standards that define what "one unit" of separation means.

9.4 "Information is physical" recast as a constraint on allowable closures

"Information is physical" becomes sharp in this framework because closure is no longer a free parameter. If information grounds geometry, then the closure mapping must respect physical constraints on information processing.

At minimum, closure must obey constraints of the following form:

- **No free distinguishability:** you cannot define a meter in a way that implies extracting distinguishability beyond what admissible measurements allow. If closure assigns meters in a manner inconsistent with operational distinguishability limits, it is physically incoherent.
- **Data-processing consistency:** admissible coarse-graining should not increase informational distance. If a proposed closure implies that "meters get smaller" under a processing step that provably discards information, the closure is suspect.

- **Resource realism:** if defining a meter requires probes of infinite energy, infinite time, or unattainable coherence, then the closure is not physically meaningful for internal observers. This is especially important in a cosmological context: closure must make sense across epochs and environments, not only in idealized labs.
- **Cross-standard universality:** physicality means that multiple realizations of standards—atomic clocks, cavity clocks, condensed-matter rods—must agree within bounded error in the macroscopic domain. If closure can be chosen independently for each standard type, "meters" lose universality and the theory risks becoming unfalsifiable.

Recasting "information is physical" this way is a significant conceptual gain. It moves the phrase from inspiration to constraint: information-first geometry demands that metrology be compatible with the real physics of measurement, recording, and resource limits. Closure is not merely a definition; it is a claim about how the world allows stable standards to exist.

9.5 The new split: informational structure vs metrological scale

We can now summarize the foundational rearrangement the paper proposes.

- **Informational structure** is what is recoverable from records, distinguishability, causal order, and admissible probes. Its natural geometric output is conformal: cones, angles, adjacency, and unitless local geometry. This layer is the candidate "it" that comes from bit/qubit: a relational backbone accessible without an external ruler.
- **Metrological scale** is what comes from choosing standards (rods and clocks) and specifying coupling rules that select a representative metric in meters and seconds. This layer is not optional, but it is also not reducible to pure counting unless additional axioms are supplied. It is where cosmological expansion becomes "relative scale drift," and where the claim "bound systems do not expand" becomes a testable statement about the stability and universality of standards.

This split offers a cleaner interpretation of both quantum foundations and cosmology. In quantum foundations, measurement is reinterpreted as record-making that provides the raw material for geometry. In cosmology, expansion is reinterpreted as drift in the closure mapping rather than growth relative to an external space. And across both, "It from Qubit" becomes attractive not because it magically yields meters, but because it supplies stronger constraints on admissible probes and more canonical notions of distinguishability—making the conformal backbone less arbitrary.

The cost of this split is philosophical modesty: it refuses to claim that information alone delivers a unique meter stick. The benefit is scientific discipline: it produces a program with internal consistency tests, cross-standard drift measurements, and falsification criteria. If this

architecture is right, then the deepest bridge between information and geometry is not “one bit equals one Planck area,” but a two-layer structure: cones from information, meters from closure—closure constrained by the physics of measurement itself.

10. Conclusion: From Metaphor to Schema

This paper began with a frustration that is easy to miss because the slogans are so compelling. “It from Bit” and “It from Qubit” are persuasive as metaphors: they tell us that reality is, in some sense, informational. But when we demand a meter stick—when we demand a disciplined bridge between dimensionless information and dimensional geometry—the metaphor stops. What we typically get instead is an unspoken import: Planck units, black-hole entropy arguments, or other moves that quietly smuggle scale back in. You explicitly rejected that move. The goal here was therefore not to win a debate about quantum gravity, but to build a structure that can state the problem cleanly and move it into the domain of testable work.

The resulting proposal is intentionally modest and intentionally sharp: information can plausibly recover **cones**—causal order and conformal structure—while **meters** enter through a separate, explicit **metrological closure axiom** tied to rods and clocks. This two-layer schema does not solve everything. It solves the category error. It gives us a place to put the meter stick without pretending it fell out of counting.

10.1 Restating the two-layer model: bridge law plus closure axiom

The model has two layers, each with a different job and different falsifiability conditions.

Layer 1: Bridge law (Conformal-from-Information).
Take as primitive: events, outcomes, admissible probes, and distinguishability relations; add causal order as the backbone. From these, reconstruct a conformal class of metrics [g]—the light-cone structure, causal topology, and unitless local geometric “shape” derived from distinguishability in the small-displacement regime. This layer aims to produce geometry-like structure *without units* and to do so robustly: patchable across regions, stable under coarse-graining, and largely probe-independent in macroscopic limits.

Layer 2: Metrological closure axiom (How meters enter).
Select physical standards (rods and clocks) and specify coupling rules that determine a representative metric g_phys within [g] by fixing a scale field Omega(x). Closure is not a decorative definition; it is a physical claim about how standards read the informational substrate and why different standard families converge. Closure may allow a running effective scale l_eff(scale)—but only if that running is constrained, universal in the appropriate limits, and measurable as cross-standard drift.

In this architecture, the "Gödel-like" underdetermination you pointed to becomes a feature rather than a defect: scale is precisely the degree of freedom that is underdetermined by informational structure alone, and closure is the disciplined locus where that degree of freedom is specified and tested.

10.2 What is gained: a clean place to put the meter stick

Three gains follow immediately.

1. **Conceptual hygiene:**
   The framework separates *structure* from *scale*. Cones and causal relations can be reconstructed from information-like primitives; meters are introduced only when standards are chosen. This prevents the common slide from "information constrains geometry" to "information fixes Planck-length meters" without stating the missing assumptions.

2. **A non-Planck route to metrology:**
   By treating closure as explicit and grounded in actual standards (atomic transitions, cavity modes, condensed-matter scales), the program shows how meters can enter without invoking black-hole entropy patches. Planck may reappear later as an emergent or limiting scale in some regimes, but it is no longer the hidden crutch that makes the whole program seem complete when it is not.

3. **A research program with testable joints:**
   Once the two layers are separated, tests become clearer. The bridge law is tested by patching, probe universality, Lorentz-like cone stability, and convergence under refinement. Closure is tested by cross-standard comparisons and drift constraints. Cosmological expansion becomes a question of relative scale drift, not an untestable statement about an outside ruler. Each part can fail in identifiable ways.

This is the main point: the schema turns a philosophical dilemma into an experimentally organized set of claims. Even if the program ultimately fails, it fails as physics should fail—by identifiable contradictions and nonconvergences—not by endless reinterpretation.

10.3 What remains open: uniqueness, universality classes, and dynamical closure

The schema does not finish the job. It tells us where the missing piece lives, but it leaves several core questions open—open in productive, researchable ways.

1. **Uniqueness of reconstruction:**
   Even within a conformal class, reconstruction may not be unique without additional constraints. Which admissibility axioms and which families of probes are sufficient to

yield a stable conformal backbone? Under what conditions is [g] uniquely identified (up to acceptable gauge freedom), and when is it underdetermined?

2. **Universality classes:**
   The program implicitly predicts that "spacetime-like" conformal geometry is an emergent universality class: many microscopic probe choices and micro-metrics flow to the same macroscopic conformal structure. But universality is not guaranteed. What are the minimal conditions for universality? Are there multiple stable universality classes—multiple "spacetime phases"—distinguished by how distinguishability composes and how causal order organizes?

3. **Dynamical closure:**
   We treated closure mainly as a mapping from unitless structure to meters. But closure must also be dynamic if standards evolve, if resources constrain probes, and if cosmological conditions change. A fully developed theory must specify how Omega(x) (or l_eff(scale)) evolves and how it couples to the informational substrate. This is where something like "field equations" must be replaced by update rules governing distinguishability and record formation, while still reproducing local Lorentz-like behavior and macroscopic stability.

4. **Quantum foundations tension:**
   If measurement is record-making that enables geometry reconstruction, then the measurement problem is no longer isolated from spacetime. The framework suggests a subtle coupling: what counts as an event may depend on what counts as a record, and records depend on decoherence, redundancy, and coarse-graining. That is promising, but it is also dangerous: if the framework cannot specify event formation without circularity, it risks becoming a rebranding of interpretive puzzles. This is precisely why the formal test suite is essential.

These open questions do not weaken the schema. They are the agenda. The program is not "derive the universe from one bit." The program is "prove that a spacetime-like conformal object is reconstructible from information in a universal way, then constrain closure by metrology and symmetry."

10.4 Forward work: a reference implementation, shared benchmarks, and a community test suite

To move from paper to practice, forward work must be organized around reproducible artifacts. The most important deliverable is not another metaphor. It is infrastructure.

1. **A reference implementation:**
   A minimal open specification (conceptually, even if not yet software) that takes event

records and probe definitions as input and outputs: inferred causal order, a conformal geometry representation, probe-dependence diagnostics, coarse-graining convergence curves, and (optionally) closure parameters with uncertainty. The implementation must include explicit admissibility assumptions and resource constraints.

2. **Shared benchmarks:**
   A suite of controlled datasets—synthetic and experimental—where the "ground truth" is known in some regimes and unknown in others. Synthetic benchmarks test whether the reconstruction can recover known conformal structure under noise and limited probes. Experimental benchmarks test cross-standard stability and drift under real apparatus constraints.

3. **A community test suite:**
   Formalize the internal consistency tests as pass/fail criteria: patching, gluing, Lorentz-like cone isotropy, convergence under refinement, probe universality at macroscales, and "closure must not alter cones." Publish these as a checklist that any proposed bridge law must satisfy to be taken seriously.

4. **A falsification culture:**
   Most importantly, the community must treat failure modes as first-class results. If certain probe families are underconstrained, if universality fails, or if closure leaks into cone structure, those are not embarrassments—they are the data that tells us where the information-first stance breaks or where it must be refined.

That is how the metaphor becomes a schema: not by asserting that information "is" reality, but by building a disciplined architecture in which information reconstructs a robust conformal backbone, metrology introduces scale explicitly through closure, and both layers are subjected to shared tests that can actually kill the claim. If this program succeeds, it will not merely clarify It-from-Bit or It-from-Qubit. It will clarify what it has always lacked: an honest, operational bridge between counting and measuring—between information and meters—without hiding the ruler inside the assumptions.

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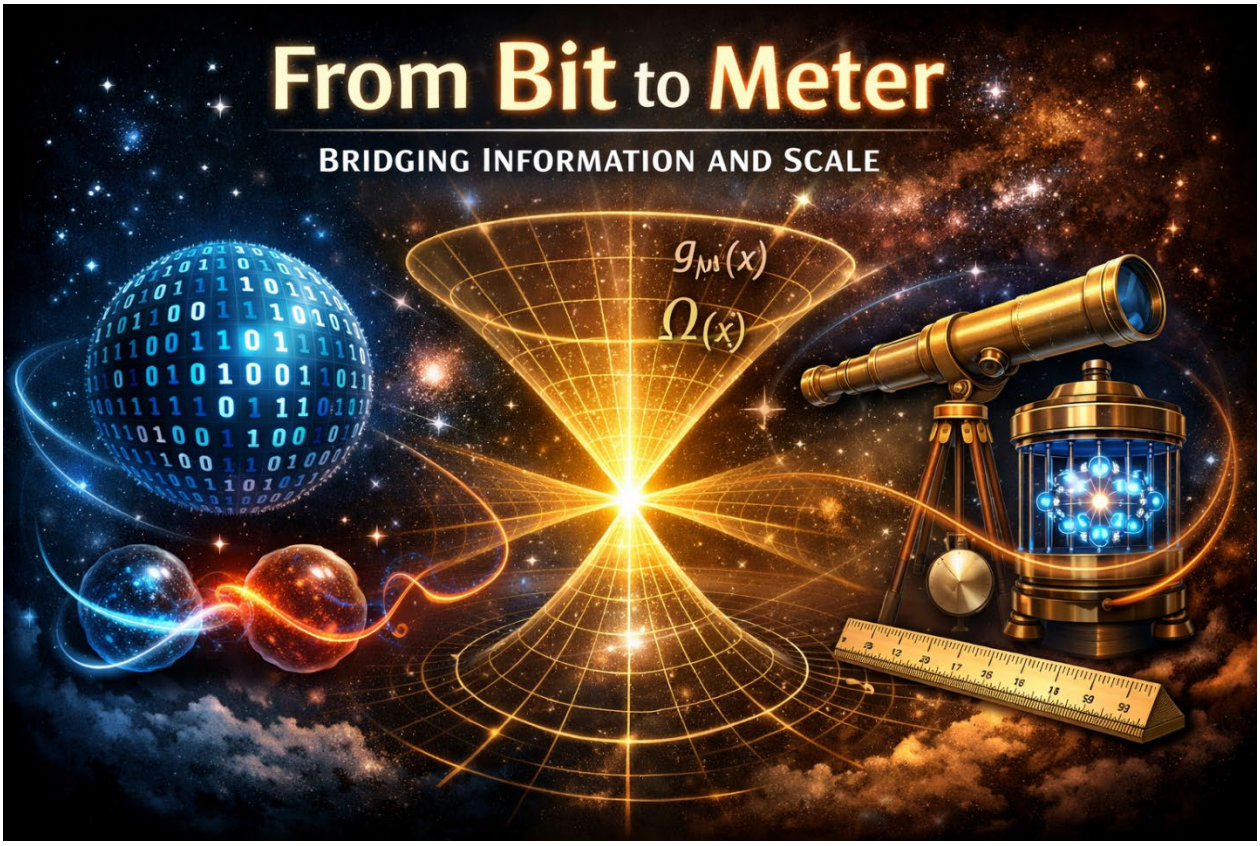
From Bit to Meter
BRIDGING INFORMATION AND SCALE
$g_{\mu\nu}(x)$
$\Omega(x)$